

# ***D*-mesons: In-medium effects at FAIR**

L. Tolós<sup>1,2,3\*</sup>, J. Schaffner-Bielich<sup>2</sup> and H. Stöcker<sup>2,3</sup>

<sup>1</sup> *Gesellschaft für Schwerionenforschung, Planckstrasse 1, 64291 Darmstadt*

<sup>2</sup> *Institut für Theoretische Physik, Johann Wolfgang Goethe Universität,  
Max-von-Laue 1, 60438 Frankfurt am Main*

<sup>3</sup> *FIAS, Johann Wolfgang Goethe Universität,  
Max-von-Laue 1, 60438 Frankfurt am Main*

(Dated: September 22, 2005)

## Abstract

The *D*-meson spectral density at finite temperature is obtained within a self-consistent coupled-channel approach. For the bare meson-baryon interaction, a separable potential is taken, whose parameters are fixed by the position and width of the  $\Lambda_c(2593)$  resonance. The quasiparticle peak stays close to the free *D*-meson mass, indicating a small change in the effective mass for finite density and temperature. However, the considerable width of the spectral density implies physics beyond the quasiparticle approach. Our results indicate that the medium modifications for the *D*-mesons in nucleus-nucleus collisions at FAIR (GSI) will be dominantly on the width and not, as previously expected, on the mass.

*PACS:* 14.40.Lb, 14.20.Gk, 21.65.+f

*Keywords:* *DN* interaction,  $\Lambda_c(2593)$  resonance, coupled-channel self-consistent calculation, *D*-meson spectral density, finite temperature

---

\* e-mail: l.tolos@gsi.de

## I. INTRODUCTION

Understanding the properties of matter under extreme conditions of density and temperature is a topic of high interest over the last years due to the direct implications in heavy-ion experiments as well as in the study of astrophysical compact objects like neutron stars. The CBM experiment of the proposed project FAIR (Facility for Antiproton and Ion Research) at GSI (Darmstadt) [1] will investigate highly compressed nuclear matter, permitting the exploration of the QCD phase diagram in the region of high-baryon densities. In particular, the research program will be focused in obtaining the in-medium modifications of hadrons in dense matter, such as mesons containing charm or anti-charm quarks [2, 3].

The medium modifications of mesons with charm, such as  $D$  and  $\bar{D}$  mesons, have been object of recent theoretical interest [4, 5, 6, 7, 8, 9] due to the consequences for  $J/\Psi$  suppression, as observed at SPS energies by the NA50 collaboration [10]. Furthermore, changes in the properties of the charmed mesons will have a strong effect on the predicted open-charm enhancement in nucleus-nucleus collisions [11, 12]. However, the open-charm enhancement is a matter of recent debate, since the latest results on dimuon production by the NA60 collaboration are not consistent with an enhancement of open-charm [13].

A phenomenological estimate based on the quark-meson coupling (QMC) model predicts an attractive  $D^+$ -nucleus potential at normal nuclear matter density  $\rho_0$  of the order of -140 MeV [4]. The  $D$ -meson mass shift has also been studied using the QCD sum-rule (QSR) approach [5, 6]. Due to the presence of a light quark in the  $D$ -meson, the mass modification of the  $D$ -meson has a large contribution from the light quark condensates. A mass shift of -50 MeV at  $\rho_0$  for the  $D$ -meson has been suggested [5]. A second analysis, however, predicts only a splitting of  $D^+$  and  $D^-$  masses of 60 MeV at  $\rho_0$  because the uncertainties to which the mass shift is subject at the level of the unknown  $DN$  coupling to the sector of charmed baryons and pions [6]. The mass modification of the  $D$ -meson is also addressed using a chiral effective model in hot and dense matter [8]. Similar results to the previous works on QMC model or QSR are obtained at  $T=0$  with the interaction lagrangian of chiral perturbation theory. However, a larger mass drop is observed ( $\sim$ -200 MeV) at  $T=0$  when a  $SU(4)$  chiral effective model is used. In this case, the attraction is reduced to  $\sim$ -150 MeV at  $T=150$  MeV.

In all these investigations, the  $D$ -meson spectral density in dense matter is not studied. In our previous work [9], the  $D$ -meson spectral density is obtained by including coupled-channel

effects as well as the dressing of the intermediate propagators, which are not considered in the QMC models, the QSR approach or the chiral effective models. These effects turn out to be crucial for describing the  $D$ -meson in dense matter [9], as already pointed out for the  $\bar{K}$  meson in the nuclear medium [14, 15, 16, 17]. Thus, the attraction felt by the  $D$ -meson is strongly reduced, as reported in [9].

In this letter, the spectral density for the  $D$ -meson not only at finite density but also at finite temperature is studied using a self-consistent coupled-channel  $G$ -matrix calculation. The medium effects at finite temperature like the Pauli blocking on the nucleons in the intermediate states and the effects coming from the dressing of the  $D$ -mesons and nucleons are investigated. Our calculation indicate that the in-medium properties of  $D$ -mesons in heavy-ion collisions will be dominantly on the width and not on the mass, contrary to previous expectations [12]. Therefore, open-charm enhancement will only be observed at FAIR if the off-shell behaviour of the  $D$ -mesons in this hot and dense matter is taken into account.

## II. FORMALISM

In this section, we extend the model of Ref. [9] to finite temperature. We calculate the single-particle potential of the  $D$ -meson at finite temperature in symmetric nuclear matter by performing a self-consistent coupled-channel calculation taking, as the bare  $DN$  interaction, a separable potential model for s-wave. The parameters of this model, i.e, coupling constants and cutoffs, are determined by fixing the position and the width of the  $\Lambda_c(2593)$  resonance. We only allow for the transition to channels with up, down and charm-quark content keeping SU(3) symmetry, since these are the channels lying close to the  $DN$  threshold (see Ref. [9]).

The introduction of temperature in the  $G$ -matrix calculation affects the Pauli blocking of the nucleons in the intermediate states together with the dressing of  $D$ -mesons and nucleons. The  $G$ -matrix equation at finite  $T$  reads formally as

$$\langle M_1 B_1 | G(\Omega, T) | M_2 B_2 \rangle = \langle M_1 B_1 | V | M_2 B_2 \rangle + \sum_{M_3 B_3} \langle M_1 B_1 | V | M_3 B_3 \rangle \frac{Q_{M_3 B_3}(T)}{\Omega - E_{M_3}(T) - E_{B_3}(T) + i\eta} \langle M_3 B_3 | G(\Omega, T) | M_2 B_2 \rangle, \quad (1)$$

where  $V$  is the separable potential and  $\Omega$  is the starting energy. In Eq. (1),  $M_i$  and  $B_i$  represent, respectively, the possible mesons ( $D$ ,  $\pi$ ) and baryons ( $N$ ,  $\Lambda_c$ ,  $\Sigma_c$ ), and their

corresponding quantum numbers, such as coupled spin and isospin, and linear momentum. The function  $Q_{M_3B_3}(T)$  stands for the Pauli operator. For the  $DN$  states, the Pauli operator reads  $Q_{DN}(T) = 1 - n(k_N, T)$ , where  $n(k_N, T)$  is the nucleon Fermi distribution at the corresponding temperature, while the Pauli operator is unity for the rest of the meson-baryon states.

In this work, not only  $D$ -mesons but also nucleons are dressed accordingly. The nucleonic spectrum at finite  $T$ ,  $E_N(k_N, T)$ , and chemical potential,  $\mu$ , that enters in the Fermi distribution, are obtained from a temperature-dependent Walecka-type  $\sigma - \omega$  model with density-dependent scalar and vector coupling constants (for details see Ref. [17]). The  $D$ -meson potential at a given temperature is then calculated according to

$$U_D(k_D, E_D, T) = \int d^3k_N n(k_N, T) \langle DN | G_{DN \rightarrow DN}(\Omega = E_N + E_D, T) | DN \rangle . \quad (2)$$

As already pointed out for the case of  $T=0$ , this is a self-consistent problem for the  $D$ -meson potential, since the effective interaction  $G$  depends on the  $D$ -meson single-particle energy, which in turn depends on the  $D$ -meson potential.

After achieving self-consistency for the on-shell value  $U_D(k_D, E_D, T)$ , one can obtain the complete energy dependence of the self-energy  $\Pi_D(k_D, \omega, T)$  by

$$\Pi_D(k_D, \omega, T) = 2\sqrt{m_D^2 + k_D^2} U_D(k_D, \omega, T) . \quad (3)$$

This self-energy can then be used to determine the  $D$ -meson single-particle propagator in the medium

$$D_D(k_D, \omega, T) = \frac{1}{\omega^2 - m_D^2 - k_D^2 - 2\sqrt{m_D^2 + k_D^2} U_D(k_D, \omega, T)} , \quad (4)$$

and the corresponding spectral density is

$$S_D(k_D, \omega, T) = -\frac{1}{\pi} \text{Im } D_D(k_D, \omega, T) . \quad (5)$$

This simplified self-consistent scheme proved to be sufficiently good for the  $\bar{K}$  case, as already shown in Refs. [16, 17].

### III. RESULTS

We start this section by discussing the effect of finite temperature in the  $D$ -meson spectral density. In Fig. 1 the  $D$ -meson spectral density at zero momentum is shown as a function

of the  $D$ -meson energy, for different densities at  $T=120$  MeV, for a cutoff  $\Lambda = 1$  and a coupling constant  $g^2 = 13.4$ , one of the sets of parameters that reproduce the position and width of the  $\Lambda_c(2593)$  resonance (see Ref. [9]). The temperature is chosen in accord with the expected temperatures for which  $D$ -mesons will be produced at FAIR. The spectral density at zero temperature for nuclear matter saturation density,  $\rho_0 = 0.17 \text{ fm}^{-3}$ , has also been included. Note that for our present results we have performed a self-consistent treatment for the  $D$ -meson potential dressing not only the  $D$ -mesons but also the nucleons in the intermediate states. This calculation lies in between the two limiting calculations performed at zero temperature [9], where only the  $D$ -mesons, or, respectively, the  $D$ -mesons, nucleons and pions were dressed. As compared to these previous calculations at zero temperature, we observe an increased attraction of -23 MeV for  $\rho_0$  at  $T=0$ , due to the attractive potential felt by the nucleon, which moves the  $DN$  threshold to lower energies, i.e. closer to the  $\Lambda_c(2593)$  resonance.

Once finite temperature effects are included, the quasiparticle peak of the spectral density for  $k_D = 0$ , defined as  $E_{qp}^2 = m_D^2 + 2m_D \text{Re}U_D(k_D = 0, \omega, T)$ , moves closer to the free mass. This expected behaviour is due to the fact that the Pauli blocking is reduced with increasing temperature since the Fermi surface is smeared out with temperature. This behaviour was already reported for the case of  $\bar{K}$  mesons [17, 18]. Furthermore, structures present in the spectral distribution are also washed out with increasing temperature. This is the case for the structure observed at energies around 1700 MeV for  $\rho_0$ , which corresponds to the  $\Lambda_c(2593)$ -hole excitation. This situation is similar to the case of the  $\bar{K}N$ , where the hyperon-hole excitations were also diluted at finite temperature [17]. Note that only the  $D$ -meson spectral density at zero momentum has been shown, since a smooth dependence in momentum is obtained. Furthermore, the  $D$ -mesons produced in central nucleus-nucleus collisions have only small momenta in the rest frame of the hadronic fireball [12].

At finite density but zero temperature, works based on the QMC model [4] and QCD sum-rules [5] predict an attractive  $D^+$ -nucleus potential with depths ranging from -50 to -140 MeV. These results are comparable to the ones obtained from an interaction lagrangian based on chiral perturbation theory, as reported in Ref. [8]. However, in the same work, when an effective chiral Lagrangian model is used, an even larger drop of the  $D$ -meson mass at  $T=0$  is obtained ( $\sim$ -200 MeV). This investigation also addresses finite temperature effects, which reduce the attraction to -150 MeV for the latter case. In the present calculation, the

coupled-channel effects, together with the self-consistent treatment of the  $D$ -meson mass, are responsible for the reduced attraction felt by the  $D$ -meson (-23 MeV for  $\rho_0$  at  $T=0$ ), as reported in our previous work [9]. The self-consistent coupled-channel effects result in an overall reduction of the in-medium modifications independently of the in-medium properties of the intermediate states [9]. The previous works based on QCD sum-rules, QMC models or chiral effective lagrangians do not considered this coupled-channel structure and, therefore, do not generate dynamically the  $\Lambda_c(2593)$  resonance. However, only a detailed comparison between models will be possible once the basic assumptions of each model, which are based on the unknown  $DN$  interaction, will be constrained by the experimental data. Furthermore, finite temperature effects result in a less attractive  $D$ -meson potential. At zero momentum,  $D$ -mesons at  $\rho_0$  and  $T=120$  MeV interact with only a few MeVs of attraction.

We have also obtained the decay width of  $D$ -mesons in nuclear matter, which has not been studied in previous calculations [4, 5, 6, 8]. We observe a considerable broadening of the spectral density as density increases at  $T=120$  MeV due to the different decay channels. The strength of the spectral density at the quasiparticle peak is reduced by a factor of about three when the density changes from  $\rho_0$  to  $3\rho_0$ . Therefore, we conclude that the spectral density of  $D$ -mesons in a hot and dense medium develops a considerable width, while the quasiparticle peak stays close to the free mass.

In order to better visualize the previous discussion, we plot in Fig. 2 the evolution of the quasiparticle peak together with the width of the  $D$ -meson spectral density as a function of the temperature for different densities (up to three times normal nuclear matter density). For zero temperature, we observe a change of the  $D$ -meson mass with respect to its free value between -23 MeV for  $\rho_0$  and -76 MeV for  $3\rho_0$ . For higher temperatures, the quasiparticle peak gets close to the  $D$ -meson free mass (-1 MeV for  $T=120$  MeV and  $\rho_0$ ). The width turns out to be sizable and varies smoothly with temperature. The width at  $T=120$  MeV increases from 52 MeV to 163 MeV running from  $\rho_0$  to  $3\rho_0$ .

The reduced attraction felt by the  $D$ -meson in hot and dense matter together with the large width observed have important consequences for the  $D$ -meson production in the future CBM experiment at FAIR. A calculation for open charm within the HSD transport approach in Au+Au collisions at 25 AGeV [12], which might be accessible at FAIR, suggests an enhancement of the  $D$ -meson yield by about a factor of 7 compared to the bare-mass case [12], using the  $D$ -meson mass shift predicted by QCD sum-rules [5]. Our present calculation

at  $T=0$  predicts that the  $D$ -meson in nuclear matter feels an attraction of -23 MeV at  $\rho_0$ , roughly half of the  $D$ -meson mass shift obtained by QCD sum-rules. Furthermore, finite temperature effects dramatically decrease this value to only a few MeVs of attraction for  $T=120$  MeV. Therefore, if only the in-medium mass shift is considered, the  $D$ -meson yield is expected to lie very close to the free case. The inclusion of a considerable width of the  $D$ -meson in the medium could lead to an enhanced production. This effect should be then the object of further analysis.

The importance of the  $\Lambda_c(2593)$  resonance for the  $D$ -meson subthreshold production as well as the magnitude of the elastic  $D$ -meson cross sections close to  $DN$  threshold can be easily inferred from Fig. 3. This figure shows the elastic in-medium transition rates for  $D^+n$  ( $D^0p$ ), the counterparts in the charm sector of  $\bar{K}^0n$  ( $K^-p$ ), from  $\rho_0$  to  $3\rho_0$  at  $T=120$  MeV as a function of the center-of-mass energy. The in-medium transition rates are calculated from the off-shell in-medium  $G$ -matrix elements at finite temperature according to

$$P_{M_i+B_i \rightarrow M_f+B_f}(s) = \int d\cos(\theta) \frac{1}{(2s_{M_i}+1)(2s_{B_i}+1)} \sum_i \sum_\alpha G^\dagger G \quad (6)$$

where  $M$  and  $B$  represent the initial and final meson-baryon states. The sums over  $i$  and  $\alpha$  run over initial and final spins, while  $s_{M_i}, s_{B_i}$  are the spins of the particles in the entrance channel. Once the transition rates are known, the cross sections can be easily determined by multiplying with the phase space available.

We observe an enhanced transition rate for energies around the  $\Lambda_c(2593)$  resonance mass. The maximum enhancement is reduced by a factor of about 4 as density increases from  $\rho_0$  to  $3\rho_0$ . This is a consequence of the dilution of the  $\Lambda_c(2593)$  as the density is increased. This has been observed for the  $\Lambda(1405)$ , which is the counterpart of the  $\Lambda_c(2593)$  resonance in the strange sector [14, 15, 17]. On the other hand, the transition rates close to the  $DN$  threshold are very small. This leads to cross sections on the order of 1 mb for the range of densities studied. This is in contrast to what is obtained, for example, for the  $K^-p$  elastic cross section. The  $\Lambda_c(2593)$  lies about 200 MeV below the  $DN$  threshold and, therefore, does not drive the behaviour of the cross sections at low momenta, contrary to the  $\Lambda(1405)$  for the  $\bar{K}N$  case. Larger cross sections (on the order of 10 mb) for the  $D/\bar{D}$  mesons with mesons and baryons have been used in order to account for the open-charm production in nucleus-nucleus collisions [12]. This is based on predictions of elastic cross sections for the  $D$  and  $D^*$  scattering with mesons [19]. Therefore, further studies of the in-medium  $D$ -meson

cross sections for the  $D$ -meson production at FAIR are needed.

#### IV. CONCLUSIONS

We have performed a microscopic self-consistent coupled-channel calculation of the spectral density of a  $D$ -meson embedded in symmetric nuclear matter at finite temperature, assuming a separable potential for the s-wave  $DN$  interaction. The parameters for the separable potential, such as coupling constants and cutoffs, have been fitted to reproduce the position and width of the  $\Lambda_c(2593)$  resonance.

The quasiparticle peak of the  $D$ -meson spectral density at finite temperature stays close to its free position for the range of densities analyzed (from  $\rho_0$  up to  $3\rho_0$ ) while the spectral density develops a considerable width. Therefore, the quasiparticle picture might not be a reasonable approximation at high temperature. On the other hand, the small shift of the  $D$ -meson mass in the nuclear medium is in stark contrast with the large changes (-50 to -200 MeV) claimed in previous works, based on QCD sum-rules, QMC models or chiral effective lagrangians [4, 5, 6, 8]. In our model, the self-consistent coupled-channel effects result in an overall reduction of the in-medium modifications independently of the in-medium properties of the intermediate states. Furthermore, this self-consistent coupled-channel calculation also allows for the determination of the decay width of the  $D$ -meson, which was not reported in previous calculations.

However, the present coupled-channel approach to the  $D$ -meson properties in the nuclear medium at finite temperature is, as the first of its kind, exploratory and can be meliorated by improving the bare hadronic interaction. An extension of our SU(3) model for up, down and charm-quark content to a SU(4) model that incorporates other channels with strange-quark content deserves further investigation. The introduction of chiral constraints for energies close to the  $DN$  threshold is also an interesting topic that is left for future work.

The in-medium effects devised in this work can be studied in heavy-ion experiments at the future International Facility at GSI. The CBM experiment will focus on the investigation of open charm [2, 3]. Our results imply that the effective masses of  $D$ -mesons, however, may not be drastically modified in dense matter at finite temperature, but  $D$ -mesons develop an important width in this hot and dense environment. Therefore, the abundance of  $D$ -mesons in nucleus-nucleus collisions should be calculated in transport theory beyond the



quasiparticle picture. Our calculation indicates that the medium modifications to the  $D$ -mesons in nucleus-nucleus collisions will be dominantly on the width and not, as previously reported, on the mass.

### **Acknowledgments**

The authors are very grateful to A. Ramos and A. Kostyuk for critical reading of the manuscript, and P. Senger for useful discussions. L.T. wishes to acknowledge the financial support from the Alexander von Humboldt Foundation (AvH) and the Gesellschaft für Schwerionenforschung (GSI).

- 
- [1] See <http://www.gsi.de/fair/experiments/CBM>
  - [2] Letter of Intent for the Compressed Baryonic Matter Experiment at the Future Accelerator Facility in Darmstadt, Darmstadt, January 2004 (<http://www.gsi.de/fair/experiments/CBM/5docu.html>)
  - [3] P. Senger, *Proceedings of the 30th International Workshop on Gross Properties of Nuclei and Nuclear Excitation: Hirscheegg 2002: Ultrarelativistic Heavy Ion Collisions*, Hirscheegg, Austria, 13-19 Jan 2002, published in \*Hirscheegg 2002, Ultrarelativistic heavy-ion collisions\*, p. 55
  - [4] K. Tsushima, D. H. Lu, A. W. Thomas, K. Saito, and R. H. Landau, Phys. Rev. C **59**, 2824 (1999); A. Sibirtsev, K. Tsushima, and A. W. Thomas, Eur. Phys. J. A **6**, 351 (1999).
  - [5] A. Hayashigaki, Phys. Lett. B **487**, 96 (2000).
  - [6] P. Morath, W. Weise and S. H. Lee, *Proceedings of the 17th Autumn school on QCD: Perturbative or Nonperturbative?* Lisbon 1999, edited by L. S. Ferreira, P. Nogueira, and J. I. Silva-Marcos (World Scientific, Singapore, 2001), p. 425; W. Weise, *Proceedings of Hirscheegg '01: Structure of Hadrons: 29th International Workshop on Gross Properties of Nuclei and Nuclear Excitations*, Hirscheegg, Austria, 14-20 Jan 2001, published in \*Hirscheegg 2001, Structure of hadrons\*, p. 249
  - [7] B. Friman, S. H. Lee and T. Song, Phys. Lett. B **548**, 153 (2002).
  - [8] A. Mishra, E. L. Bratkovskaya, J. Schaffner-Bielich, S. Schramm and H. Stöcker, Phys. Rev. C **69**, 015202 (2004).
  - [9] L. Tolós, J. Schaffner-Bielich and A. Mishra, Phys. Rev. C **70**, 025203 (2004).
  - [10] M. Gonin *et al.*, NA50 Collaboration, Nucl. Phys. A **610**, 404c (1996).
  - [11] M. I. Gorenstein, A. P. Kostyuk, H. Stöcker and W. Greiner, Phys. Lett. B **509**, 277 (2001); M. I. Gorenstein, A. P. Kostyuk, H. Stöcker and W. Greiner, J. Phys. G **27**, L47 (2001); A. P. Kostyuk, M. I. Gorenstein and W. Greiner, Phys. Lett. B **519**, 207 (2001).
  - [12] W. Cassing, E. L. Bratkovskaya, and A. Sibirtsev, Nucl. Phys. A **691**, 753 (2001).
  - [13] Talk given at the XVIII International Conference on Nucleus-Nucleus Collisions (Quark Matter 2005) by E. Scomparin (INFN, Torino, Italy), on behalf of the NA60 Collaboration. See <http://qm2005.kfki.hu>

- [14] M. Lutz, Phys. Lett. B **426**, 12 (1998).
- [15] A. Ramos and E. Oset, Nucl. Phys. A **671**, 481 (2000).
- [16] L. Tolós, A. Ramos, A. Polls, and T.T.S. Kuo, Nucl. Phys. A **690**, 547 (2001).
- [17] L. Tolós, A. Ramos, and A. Polls, Phys. Rev. C **65**, 054907 (2002).
- [18] J. Schaffner-Bielich, V. Koch and M. Effenberg, Nucl. Phys. A **669**, 153 (2000).
- [19] Z. Lin, and C. M. Ko, J.Phys. G **27**, 617 (2001).

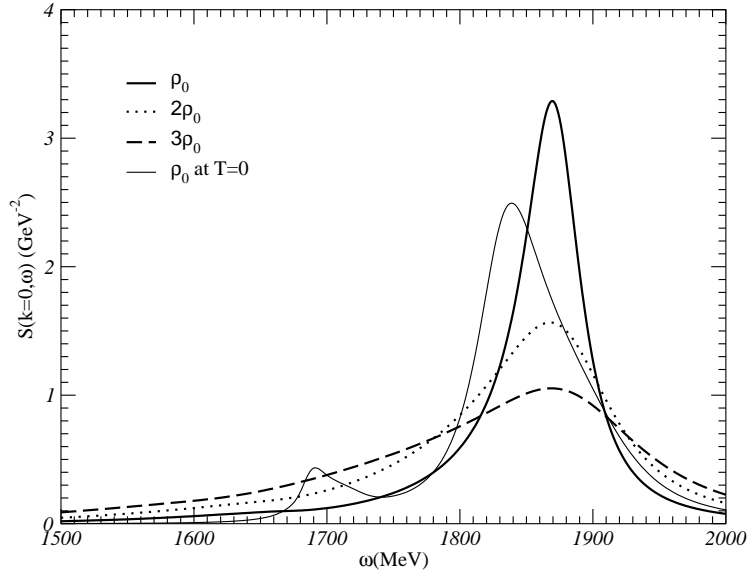


FIG. 1:  $D$ -meson spectral density at  $k_D = 0$  and  $T=120$  MeV as a function of energy for different densities, together with the  $D$ -meson spectral density at  $k_D = 0$  and  $T=0$  MeV for normal nuclear matter density  $\rho_0$ .

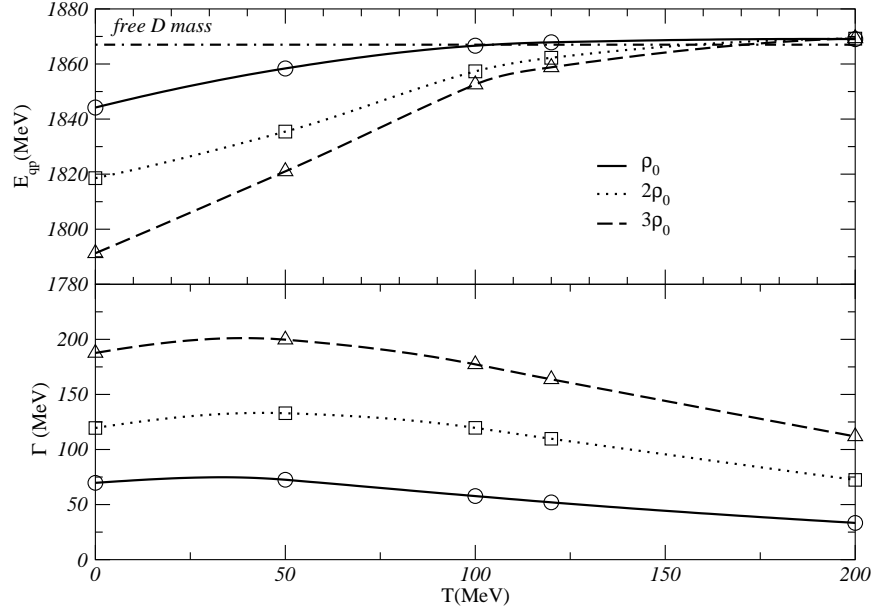


FIG. 2: Quasiparticle energy and width of the  $D$ -meson spectral density at  $k_D = 0$  as a function of temperature for different densities.

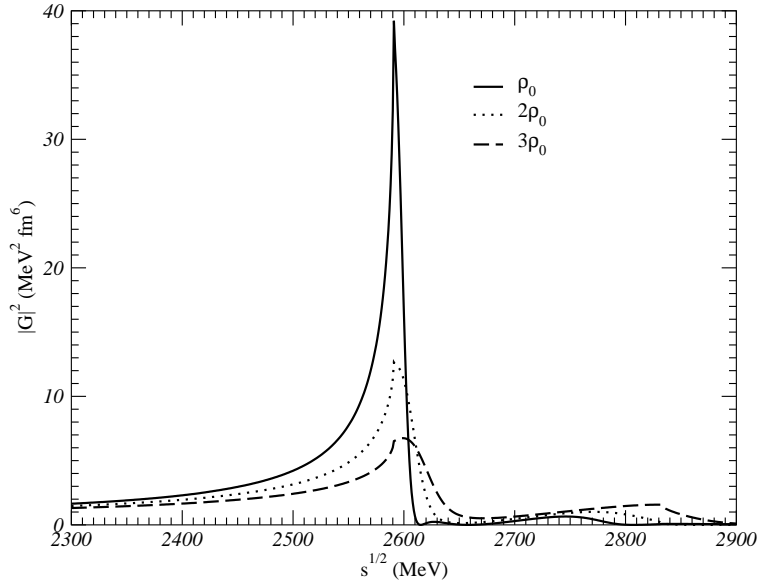


FIG. 3: In-medium transition rates for  $D^+n$  ( $D^0p$ ) at  $T=120$  MeV as a function of the center-of-mass energy for different densities.